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3D Printing Temporary Crown and Bridge by Temperature Controlled Mask Image Projection Stereolithography

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Abstract

Traditionally, the fabrication of temporary teeth restorations must go through multiple processes such as moulding, curing and post finishing, which requires extensive expertise of dentists. In addition, the handmade temporary restorations are usually unable to precisely fit the patient's teeth due to limited formability of material. To address the problem, a three-dimensional (3D) printing technology named temperature controlled mask image projection based stereolithography (TCMIP-SL) is presented for dental materials in this paper, with aim to build customized temporary crown and bridge quickly for its use in dental offices. We first studied the photo-polymerization performance of commercial materials that are commonly used in dental industry. Then we discussed the temperature effect on curing performance and rheology of dental composite material. Based on the studies, we further developed our TCMIP-SL process by integrating a material coating system with controllable heating, so that the coated thin film of dental composite material can be selectively cured using high resolution patterned light beam. Several test cases are performed to demonstrate the TCMIP-SL process can 3D print high viscous temporary crown material with fast speed and high resolution.

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1. Introduction

Around forty million provisional teeth restorations are required annually in the United States. The

temporary crown or bridges are necessary for patients to protect the prepared teeth until permanent crowns or bridges can be affixed [1]. Currently the fabrication of permanent dental crown or bridges with

material such as metal, ceramic or other high strength composite may take two or more weeks through a dental laboratory. During the preparation of permanent restorations, temporary restorations are necessary for patients because they serve for important functions including protecting teeth, preventing teeth shifting, and providing cosmetics until a final restoration can be inserted [2]. Temporary restorations are usually made of plastic (acrylic resins) in two ways. The first way is to build shells to fit patients' original teeth. The second way is to fabricate the restorations directly from scratch using the molding process [3]. However, the pre-formed temporary restorations must be further trimmed with several iterations in patient's mouth before they are cemented [3]. Throughout heavy daily usage, breakage of temporary restorations may frequently occur, and dentist must build a new one by repeating all the procedures, which requires a lot of time and effort of both patients and dentists. Nowadays, digital design and manufacturing are gradually changing the dental restoration fabrication practice. Instead of the traditional molding process, various digital mouth scanners are used to generate accurate digital orthodontic data in just minutes [4]. Based on the digital scanning data, the restoration can be designed and fabricated using advanced design and manufacturing technologies. Therefore, there is a critical need for a solution that can fabricate temporary crown within minutes based on the digitally scanned data.

Three-dimensional (3D) printing technology has been widely used in manufacturing models with complex freeform surfaces, and the geometric shape of the model fabricated by 3D printing can be easily customized based on the demands of patients. In the 3D printing processes such as fused deposition modeling (FDM), stereolithography (SL) and inkjet printing, the material is deposited layer by layer to generate the final 3D shape. Polymer based composite provisional dental materials, which provide exceptional strength, flexibility, and abrasion resistance, are widely used to fabricate temporary restorations in dental industry [5]; however, the flowability of most dental composite materials is poor due to its high viscosity and may bring difficulty to 3D printing processes [6]. In the FDM process, the nozzle is heated to melt the thermoplastic and the viscous plastics can be deposited by an extrusion head [7]. Although FDM process is a flexible printing method that can process a large range of high viscous

materials, it is limited for the temporary crown and bridge fabrication due to its limited printing resolution, surface quality and time efficiency. Using photo-curable polymer interim crowns have been fabricated by PolyJet 3D printing [8]. In the inkjet-based 3D printing process, a material disposition head goes through the entire area of the model in order to selectively accumulate material. The whole fabrication process consumes hours to fabricate millimeter height dental restorations [9]. In addition, dental restorations have also been printed using the mixture of dental porcelain powder and binder by ceramic printing process [10]. Several post-processing steps including debinding and sintering are necessary to remove the mixed binder in order to obtain the final ceramic dental restorations. In addition to the slow fabrication process, the micro-scale porous defects inside the printed restorations due to the removal of binder usually have negative impacts on the mechanical performance.

Stereolithography apparatus (SLA) is one of the main additive manufacturing (AM) technologies with high resolution and fast speed. Researchers have used it to print temporary restorations with photo-curable dental composite [11-13]. In Mask image projection based stereolithography (MIP-SL) process, a 3D object is first sliced by a set of horizontal planes; each thin slice is then converted into a two-dimensional (2D) mask image. The 2D patterned light beam controlled by the digital micromirror device (DMD) is projected onto the surface of photo-curable material. A layer of material can be cured by the 2D patterned light beam after receiving sufficient energy from light exposure. Thus a 3D object can be printed gradually by stacking each layer [14-16]. The MIP-SL process is highly efficient on fabricating macro-scale model with hundreds of layers due to its capability of fabricating one layer with a short-time illumination. The composite materials like multifunctional ceramic have also been successfully fabricated using the MIP-SL process [17]. However, the material refilling of high viscous material is one big challenge that restricts the MIP-SLA process from fabricating temporary crowns and bridges. To refilling liquid resins with high viscosity, special apparatus, e.g. blade, are necessary to achieve the uniform coating of material, and the shear force set by the blade should be sufficient to spread material into a thin layer [18, 19]. Such recoating process may cost a lot of time, which may significantly affect the efficiency of the MIP-SL process [20, 21].

The temperature of material is known to have big impact on the viscosity of polymer based composite material. The viscosity of the dental material will significantly reduce with the increase of temperature [22, 23]. In the paper, we extend our previous work on the ceramic-based MIP-SL process to the temperature controlled MIP-SL. That is, dental composite materials are cured by 2D patterned light beam in the building environment with controlled temperature. Infrared light radiation is used to uniformly heat up the composite material and the temperature of material maintains at an optimal level under close feedback control. To optimize the process parameters, we studied the rheology of photo-curable composite material at different temperatures. Based on the result, we further investigated the curing performance of photo-curable polymer based composite materials under a large range of temperature in order to identify the appropriate temperature setting. Furthermore, a new rotary movement design was implemented in the TCMIP-SL process to continuously spread viscous composite material into uniform thin layer. The developed TCMIP-SL system, in which the resolution of the light beam can reach 25 μ m per pixel, can fabricate the temporary crowns and bridges with continuous material refilling (refer to Fig.1). Hence the TCMIP-SL process can fabricate dental materials with fast building speed and high resolution. It shows significant strengths over the existing fabrication technologies of highly viscous materials, which has promising use in applications such as multifunctional ceramic fabrication and biomedical 3D printing.

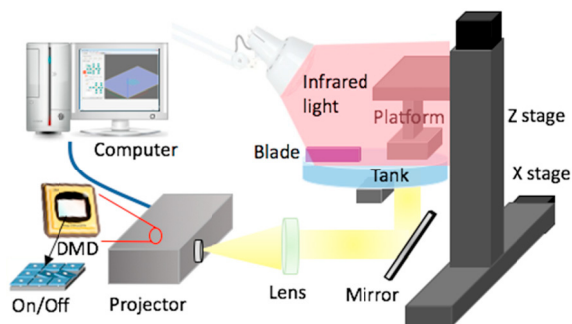


Fig. 1. The schematic diagram of 3D printing of temporary crown using TCMIP-SL process

The nomenclature of the paper is given as follows.

Nomenclature

a	the flow consistency index
c	the viscosity of the material
C_d	the cure depth of material
D_p	the penetration depth of light beam in material
E_c	the critical energy of exposure
E_{max}	the energy of exposure
g	the gap width of blade tip and transparent plate
k	the constant
L	the blade channel length
n	the flow behaviour index
ΔP	the pressure of material
γ	the shear rate
T	the temperature of material
τ	the shear stress
v	the moving speed of rotation stage
ρ	the density of the material in the film

2. Material Selection

Material for provisional restorations should possess superior material properties including good strength, long durability, and short procedure time. Additional features such as patient comfort, dimension stability, and colour stability are also considered by dentists and patients. Plenty of FDA approved materials are currently available in the dental market. Generally, there are four main types of dental materials approved by FDA: polymethylmethacrylate (PMMA), polyethylmethacrylate (PEMA), bis-acryl composite resin, and light-cure composite resin (refer to Fig. 2) [24].

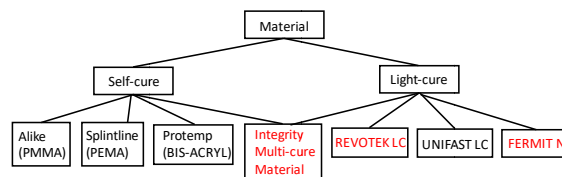


Fig. 2. The material used for temporary crowns and bridges.

We tested several light-curable dental materials in order to take advantage of high resolution MIP-SL process. Light-curable temporary crown material (from UNIFAST LC) has superior physical properties and wear resistance. However, in the room temperature, the viscosity of the material will gradually become higher than 500 mPa.s during the mixture of powder (PMMA, activator) and liquid

(MMA, hydroquinone, initiator). Due to the self-curing property of PMMA, the crosslinking of polymer will take place in minutes in the room environment, making the 3D printing of such material difficult. Moreover, the temperature-independent and irreversible polymerization characteristics of PMMA determine that the flowability cannot be improved with the temperature change.

The photo-curable bis-acrylic based composite material (from REVOTEK LC) is also high viscous composite resin that offers improved flexural strength and outstanding physical properties. In clinical practice, dentists cut this rubber-like material into small pieces, put them onto the grinded tooth, and then hand-craft the material into desired tooth shape [2]. Following that, the tooth-shaped material is solidified under sufficient light exposure. It takes dentists a relatively long time to polish the surface of cured material and adjust the shape of cured material according to the patient's tooth. In addition, we investigated another bis-acrylic based material (Integrity Multi-cure material), one type of commercialized material used for temporary crown fabrication. The composition of multi-cure material is glass filler, methacrylate monomers, catalyst, photoinitiator, and stabilizers [25]. Camphoroquinone, as photoinitiator, can help the methacrylate crosslink under the exposure of visible light with 385-405nm wavelength [26]. Similarly, dentist dispensed this material into one matrix and placed the matrix into the patient's mouth. After removing the provisional crown or bridge from the mouth, the dentist cured the crown with dental light. The cured crown was trimmed, adjusted, finished, polished, and then grinded tooth was put on. Just as other manual methods, the quality of temporary restoration mainly relies on the skills of dentists, while the additional matrix impression actually increases the complexity of crown fabrication process.

In the developed TCMPI-SL process, we selected integrity multi-cure material and ERVOTEKLC material as the test materials since the material viscosity of both materials can be reduced with increased temperature, and they are photocurable materials that can be cured under the exposure of visible light with 405nm wavelength.

3. TCMIP-SL

To address the flowability issue of bis-acrylic based temporary crown materials, we developed the temperature controlled mask image projection based

stereolithography (TCMIP-SL) process. The viscosity of the material can be reduced under increased temperature to allow continuous accumulation of material. Additionally, the higher temperature promotes the photo crosslinking reaction for the formation of a covalent bond due to more energy being supplied by the heating process [27]. Therefore, increasing the temperature of bis-acrylic based composite materials improves not only the flowability, but also the light curing performance.

3.1. Advantages of the Bottom-up based TCMIP-SL Process

In SLA process, liquid resin is selectively cured into solid using 2D patterned light beam exposure [12]. There are two typical layouts in the SLA process: the bottom-up based design configuration and the top-down based design configuration. In the top-down based printing process, the platform must be merged into the resin vat, and the light is projected down from the top. After the fabrication of a layer, the building platform must move down to refill the new layer of material [13]. However, the top-down printing layout is not a good solution for high viscosity material fabrication due to the difficulty in forming a uniform thin layer on the pre-cured layers; on the other hand, compared with the bottom-up based printing process, the top down based SLA process requires a large amount of material in fabricating the same model [14]. Due to these two drawbacks, we adopted the bottom-up based design configuration in the TCMIP-SL process, where resin between the glass window and the platform is cured by an exposure to light coming from the bottom.

3.2. Challenges of Material Refilling

For the 3D printing of temporary restoration the material refilling is a critical issue that needs to be addressed. As discussed before, the photo-curable bis-acrylic based composite material is slurry-like or rubber-like composite material. It is difficult to recoat these high viscous materials to 50-200 μm thickness thin film, which is the fundamental requirement of the 3D printing of highly viscous material. Hence several design improvements are required to achieve continuous refilling of highly viscous material. Based on the study of bis-acrylic composite, we identified that the material refilling condition and curing performance will be improved by increasing the

temperature of material. Therefore, we designed a close-loop heating system to control the temperature of the environment during the fabrication process. Moreover, a recoating blade was integrated in the mechanical system to generate a continuous layer of material on the tank. We further studied the relationship between the relative moving speed of the blade and the recoating performance. Consequently, the rotation stage can be rotated at an appropriate speed to continuously spread the material with consistent thickness on the fabrication plate.

3.3. Hardware and Software Design of TCMIP-SL

The TCMIP-SL prototype system for provisional restoration 3D printing is consisted of hardware and software modules with close-loop controlled process parameters. There are four main subsystems including heating system, optical imaging system, mechanical moving system, and material feeding system. The heating system heats up the material and maintains the whole fabrication area at a certain temperature during the fabrication process. To achieve such high temperature, high power infrared lamp was used to heat up both the material as well as the rotation plate. The viscosity of material turns to be much smaller as the temperature increases, but the slurry-like material is still unable to flow to a thin film by the air pressure and the material gravity. Thus, a material feeding system was added, i.e., a blade and the related blade adjustment system, in order to continuously coat the material with 50-100 μm thickness. The schematic diagram of the prototype machine is shown in Fig.3.

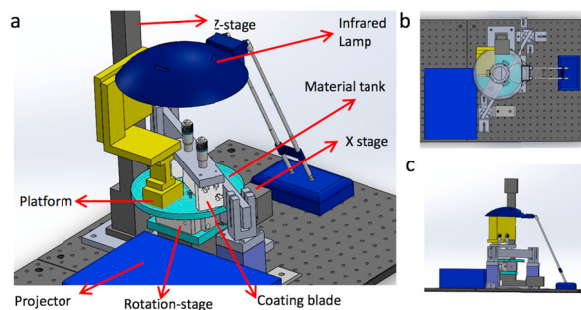


Fig. 3. The hardware design of the temporary crown and bridge 3D printing machine. (a) The description of the prototype system; (b) the top-view of the device; and (c) the side-view of the device.

In the heating system, an infrared lamp and a temperature sensor are added. A heating rubber (10

W) is pasted on the back of blade to heat up the blade. The infrared lamp (200 W) is fixed at the top of the printing area (refer to Fig.3) and a temperature sensor (DS18B20) is fixed on the back of coating blade to monitor the temperature of material. With the added temperature sensor, we can monitor and maintain the temperature of material during the fabrication process. Measurements show that the initial viscosity of material is higher than 500 mPa.s at the room temperature (22°C). The rheological properties of the material at this status are difficult for 3D printing, as the material cannot be easily refilled for the upcoming layer fabrication if no external force is applied.

To address the material refilling problem, a doctor blade used in film casting is added to our material feeding system, and a rotary stage is also added to provide continuous side movement under the inspiration of our previous work [13]. Through fine-tuning the position of blade, material at thickness of 100 μm was successfully coated on the fabrication plate during the rotation of the stage. Moreover, after the cooling down of the fabrication area to the room temperature, the recovered material resumes being rubber-like status and also maintains the photo-curable property. Therefore, the material can be recycled in the TCMIP-SL process, which is better than the traditional fabrication methods of the temporary crowns and bridges.

The optical system of TCMIP-SL contains a visible lamp, a DMD chip, a mirror, and a lens combination. As discussed before, the light intensity of the exposure area is 2500 lm, and the illumination beam is focused through a series of lens. To preserve all the energy of the lamp, the light is collimated before it irradiates to the fabrication area. The dimension of the projection image of the prototype system is 45mm×33.8mm, and the resolution of the DMD chip from Texas Instruments is 1920×1080. Hence, the resolution of the system is 24 μm /pixel.

A mask image planning testbed has been developed using the C++ language with Microsoft Visual C++ compiler. The testbed integrates the geometry slicing and the motion control. It also synchronizes the image projection with the X and Z movements. The graphical user interface of the developed software system is shown in Fig.4.

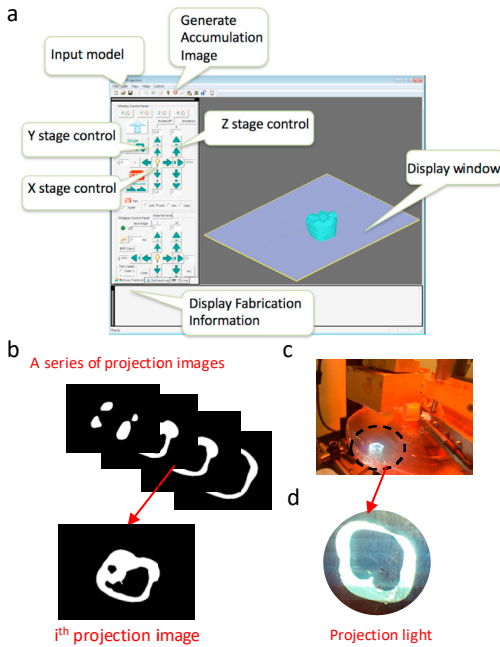


Fig. 4 The software system of the TCMIP-SLA process. (a) The GUI of the TCMIP-SLA process; (b) a series of sliced mask images, (c) a photo of the projection area; and (d) the projection light of a layer.

4. TCMIP-SL Process Development

As mentioned previously, our process has integrated heating process, doctor blade and rotary platform to address the material refilling issue of the dental composite material. In the following section, we will discuss the temperature control and continuous material recoating in the TCMIP-SL process.

4.1 Curing and Rheological Properties of Material

Infrared light lamp working at a higher temperature can transfer energy to other object with a lower temperature through electromagnetic radiation [28]. We hence used an infrared light lamp as a heater and the composite material was heated up by the uniform illumination of the infrared light lamp. To achieve stable heating of the material, we added the temperature sensor (DS18B20) to control the material temperature, and the temperature display rate is set as 2 times/s. Based on the feedback of the temperature sensor, we used the pulse width modulation (PWM) signal to control the power of the infrared heater. We applied the proportional-integral-

derivative (PID) control to maintain the material temperature at 70- 80 °C and the accuracy of our measured temperature is ±0.5 °C.

The rheological behaviours of the dental slurry material have been studied. The results show that the viscosity of the material varies with the change of temperature (refer to Fig.5). When the material temperature is below the threshold δ_g (glass transition temperature), the material is in solid state, which is impossible to form thin film. When the temperature is higher than the threshold δ_g , the viscosity of material dramatically decreases, making it easier to spread the material into a thin film by applying shearing force [29].

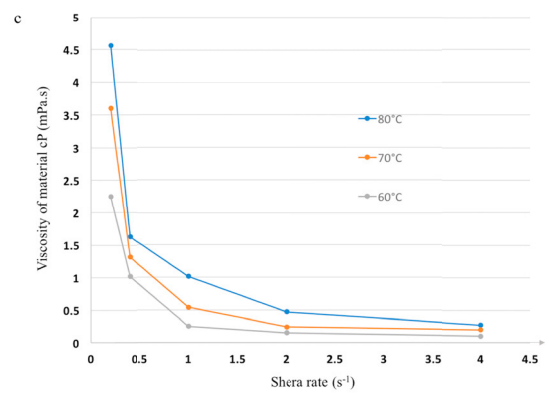
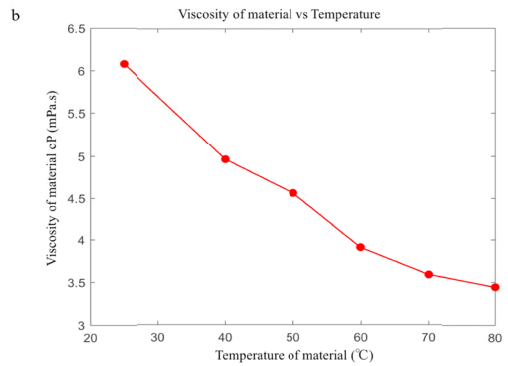
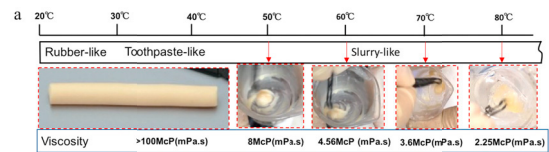


Fig. 5 The effect of temperature on the rheology of material. (a) The effect of temperature on the viscosity of REVOTEK; (b) The effect of temperature on the viscosity of Integrity multi-cure material; and (c) The effect of temperature on the rheology of REVOTEK at different shear rate.

As shown in Fig. 5a, with the increasing of temperature from 20 °C to 80 °C, the rheology of the

material changes from rubber-like status to slurring-like and the viscosity was reduced to 2.25 McP. We also conducted the same experiment to test the viscosity change of another bis-acrylic based material (Integrity Multi-cure material) by changing the temperature from 20 °C to 80 °C, and the result is shown in Fig. 5b.

The rheological tests of the dental material at different temperatures were performed using a Brookfield dial reading viscometer equipped with a small sample adapter (SC4-14/6R), and the results are shown in Fig.5c.

Because the bis-acrylic based composites are non-Newtonian and shear-thinning materials, their viscosity decreases as the increase of the shear rate [29]. The shear-thinning composite material follows the Power-law equation [29]:

$$\tau = a(T)(\gamma)^n \tag{1}$$

The viscosity of material is defined as:

$$c = \frac{\tau}{\gamma} \tag{2}$$

Substitute τ in to Eq. (2):

$$c = a(T)(\gamma)^{n-1} \tag{3}$$

The flow consistency index $a(T)$ is the function of temperature and Eq. (3) states the relationship between the composite material’s viscosity and temperature. The flow consistency index drops as the temperature increases [30].

Meanwhile, the peak of wavelength of the infrared radiation ranges from 780 nm to 1 mm, while the photo crosslink reaction is only triggered by blue light with wavelength 405 nm – 500 nm. The curing behaviour of viscous photo-curable polymer can be expressed by Beer-Lambert’s law [27]:

$$C_d = D_p \ln\left(\frac{E_{max}}{E_c}\right) \tag{4}$$

Upon receiving sufficient energy, polymer chains are formed by reacting monomer in the polymer solution [31]. We studied the curing performance of bis-acrylic based composite dental materials. At the room temperature, the relation between the cure depth and the exposure time under GC Labolight (120 W) is shown in Fig.6a.

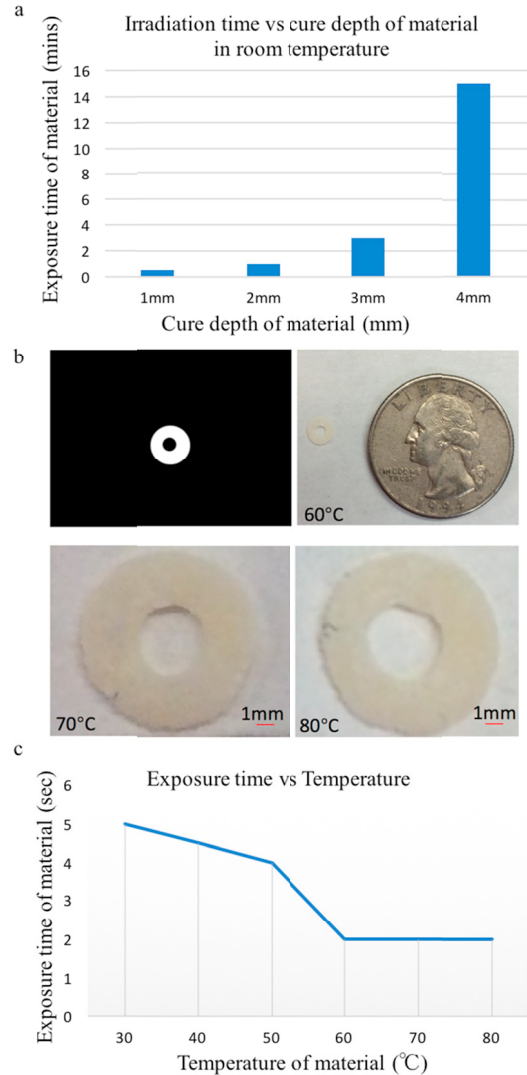


Fig. 6 The curing performance material at different temperature. (a) Cure depth of material at different irradiation time in room temperature; (b) Cured part samples at different temperatures; and (c) Exposure time of material at different temperatures.

Furthermore, to figure out the relation between the exposure time and the material temperature, we cured 8mm diameter rings using the mask image pattern as shown in Fig. 6b with the same power of light exposure (50 mw/cm²). The results of the fabricated parts at different temperature are shown in Fig. 6b. From the experimental results, we can see the cure time of the dental material is reduced slightly with the increase of temperature. The reason may be the heat energy received from the infrared light helps curing but is not sufficient to crosslink the polymer chain when compared with E_c .

Further experiments on the temperature impact to the curing properties of the dental material were conducted to study the curing behaviour at different heating conditions. As shown in Fig.6c, the exposure time of the material slightly reduced to 2s when the material temperature is increased to 60 °C. To speed up the photo-curing process and improve the flowability of the dental material at the same time, we set the temperature of material at 70 °C in the TCMP-SL process. At 70 °C, the cure time of the dental composite material is 2 s and the cure depth of the material is 200 μm.

4.2 Continuous Thin Film Coating

Blade coating, also known as knife coating or doctor blading, is a processing method for the fabrication of large area films on rigid substrates. The well-defined thickness is mainly controlled by the gap size between the blade and the substrate surface, as well as the moving speed of the blade [32, 33]. Coating parameters that influence the formation of thin film are surface energy of the substrate, coating speed, and the viscosity of the material [34]. The flow characteristics have been studied and the slurry composite we used is Non-Newtonian flow [35]. The doctor blade and the rotation tank generate a parallel channel that is considered as Couette flow. The coated layer thickness d of the composite material can be obtained by following equation [34]:

$$d = kg(1 + \frac{g^2 \Delta P}{6\mu v L}) \tag{5}$$

Fig.7 shows the principle of the material recoating method that can continuously refill highly viscous material for the layer-based fabrication process. In this recoating method, we fixed the blade with certain distance g away from the rotation stage in the Z direction (refer to Fig.7b), and a transparent plate is mounted on the rotation stage.

The 2D patterned projection light goes through the transparent plate without any blocking. As shown in Fig. 7c, the relative position between the projection area of the 2D patterned light beam and the platform where the cured layers are attached on is fixed so that there is no influence of recoating movement on the material curing process. A teflon film is attached on the transparent plate to facilitate the separation of cured layers. With the movement of the rotation stage, the dental material is continuously extruded from the gap between the blade and the transparent plate in the moving direction of the

rotation stage. Driven by the shearing force between the blade and the material, a thin layer of the dental material is recoated on the flat surface of the transparent plate [34]. Based on Eq.5, we can change the recoating thickness of the material by adjusting the moving speed of the rotation stage v and the gap width of the blade g . We heat up the commercial materials for temporary crown from REVOTEK LC. The viscosity of material was 2.25 McP at temperature 70 °C and the minimum layer thickness of the recoated film that can be achieved in our setup is 50 μm.

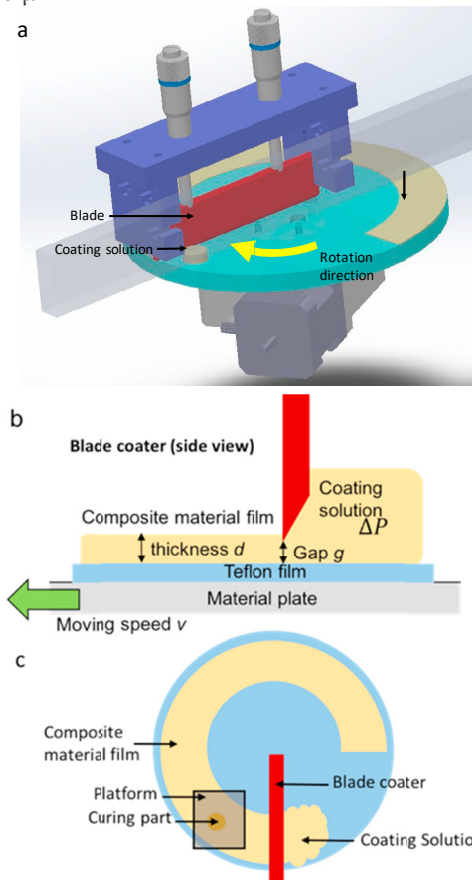


Fig.7 The schematic diagram of the continuous thin layer film recoating. (a) The rotary movement design of the continuous thin layer film recoating; (b) the side view of the thin film recoating process; and (c) the top view of the thin film recoating process.

After curing one layer, the Z stage elevates the building platform with an appropriate speed V_z , and at the same time, the rotation stage rotates forward with speed V_x , so that the thin film of material is extruded in the tangential direction from the gap between the blade and the transparent plate. Meanwhile, the sliding movement in the X direction also makes the separation of the cured layer away

from the Teflon film easier compared with directly moving up the building platform. The separation force is significantly reduced with the two-way movement especially for highly viscous materials [13, 14].

The two-way movement is hence applied to the TCMIP-SL process in fabricating temporary restoration. During the fabrication process of each layer, the Z stage moves up with a distance equal to the layer thickness, and at the same time, the rotation stage continuously rotates with an appropriate angle. The rotation angle of the stage at each layer is calculated based on the cross-section area of the 3D printing model, so that unnecessary rotary movement of the transparent plate is avoided. During the entire process, there is no relative motion between the building platform and the projection area, so the material can be accumulated on the surface of the platform layer by layer. For the fabrication of each layer, material is recoated at 50 μ m-200 μ m thickness by the forward movement of the rotation stage, saving the time from adjusting rotary plate back and forth with respect to the blade [18, 19]. Due to the single directional rotary motion, the printing efficiency of temporary crowns is improved compared with the traditional SLA-based ceramic fabrication process [8, 10, 11].

5. Experimental Results and Discussions

Tests have been conducted to verify the building speed of the developed prototyping system. The fabrication results of designed temporary crown and bridge are shown in this section. The fabrication time of each sample is compared with the traditional fabrication method with the comparison data shown in Table 1. The results show the developed TCMIP-SL process can build temporary crown and bridge in minutes instead of hours as shown in using commercial Polyjet or FDM printers [5-8]. The experimental tests also show that temporary crown and bridge with different types of geometries can be fabricated by the TCMIP-SL process, and the surface quality of the 3D printed crown is competitive with the one made by the traditional molding process.

A set of temporary restorations with different complex geometric shapes was built by the TCMIP-SL process. The fabrication results of the temporary restorations are shown in Fig.8-10. The related STL files of the 3D printing models had triangle numbers

ranging from several hundreds to 1.2 million (refer to Table 1). For all the temporary crown and bridge models, the FDA approved commercial material of temporary crown (from REVOTEK LC) was used. Its viscosity was reduced to 2.25 McP with uniformed infrared heating at 70 °C.

Table 1. Building time statistics.

Model	Incisor bridge	Second molar	lateral molar shell
Figure Num	Fig.7	Fig.8	Fig.9
Size x(in)	0.337	0.488	0.494
Thickness (um)	75	75	75
Section area (in ²)	0.255	0.209	0.058
T _{projection} (s)	10	10	15
Tz(s) [up+down]	1s	1s	1s
Tx (s)	0.2s	0.3s	0.3s
Heightz (mm)	6.3	5.7	7.35
Layer Num	84	76	98
Total_building (min)	15.4	20.3	26.3

To achieve smooth surface, we sliced the digital model and fabricated 2D layers using the layer thickness of 75 μ m in the building process. Within different regions of the projection light beam, the light intensities of each region may be slightly different; hence we applied different exposure time based on the calibration of light intensities within the projection area. For example, to get the same cure depth of material, the exposure time of solid dental restoration is 10s /layer and the exposure time is increased to 15s / layer in order to build thin shell of crown features. Likewise, the moving distance of the rotation is related to the geometric shape of 3D printing objects. We dynamically set the moving distance of the rotation stage at each layer equal to the maximum dimension of the projection area in the moving direction of the rotation stage. For the fabrication of temporary bridge, we optimized the orientation of mask image to reduce the movement distance of the rotation stage. Fig.8 shows the fabrication result of temporary bridge with the total fabrication time of 15.4 minutes.

Fig. 9 and 10 show the built temporary crowns based on the developed TCMIP-SLA process. As shown in Fig.8d, Fig.9f and Fig.10d, the quality of the fabricated objects is shown under the high magnification microscope. Fig.10f shows the wearing

effect of the 3D printed temporary crown on the dental plate. The printing parameters of each built dental part are shown in Table 1. To the best of our knowledge, our TCMIP-SL process is one of the fast additive manufacturing processes that can fabricate of highly viscous composite materials for dental applications.

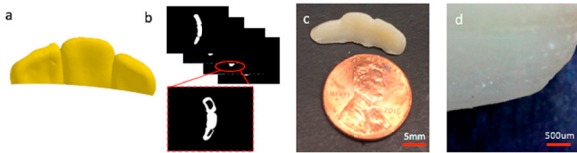


Fig.8 The 3D printed temporary bridge using the TCMIP-SL process. (a) CAD model of temporary bridge; (b) projection mask images of the temporary bridge; (c) the fabricated temporary bridge; and (d) the microscope image of the 3D printed temporary bridge.

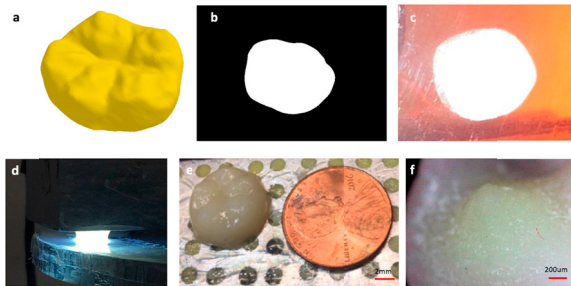


Fig.9 The 3D printed temporary second molar using the TCMIP-SL process. (a) CAD model of temporary second molar; (b) the i^{th} layer of the projection mask images to fabricate the temporary molar; (c) projected 2D patterned light beam; (d) the image taken during the fabrication process; (e) the 3D printed second molar; and (f) microscopy image of the 3D printed molar surface.

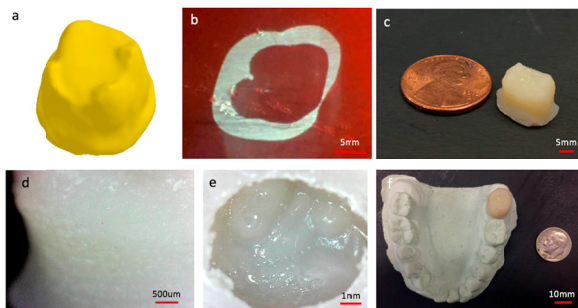


Fig.10 The 3D printed temporary lateral molar shell using the TCMIP-SL process. (a) CAD model of the temporary lateral molar shell; (b) projected 2D patterned light beam; (c) the side view of the 3D printed temporary molar shell; (d) microscopy image of 3D printed molar shell surface; (e) microscopy image of an inner surface of the molar shell; and (f) the wearing effect of the 3D printed molar shell.

6. Conclusion

A temperature controlled mask image projection based stereolithography (TCMIP-SL) process has been developed for the fabrication of highly viscous temporary crown with fast building speed. To improve the manufacturability challenges of high-viscous composite material, the uniformly distributed infrared light radiation has been applied to heat up the dental material. For quickly spreading highly viscous composite material into uniform thin layers, a recoating system with side movement and a spreading blade has been developed. The designed two-way movement also enables easier separation of cured material from the building tank. Furthermore, the material can be recycled for multiple times due to the reversible temperature dependency; hence less material is consumed than the traditional approaches. We demonstrate several fabrication test cases and the experimental results show that the newly developed TCMIP-SL process can successfully fabricate temporary restorations with satisfactory quality in a short time (usually in minutes). The TCMIP-SL process shows significant strength over the existing 3D provisional restoration fabrication methods that are used for dentists. We believe the developed TCMIP-SL process has prodigious potential and extensive foreground in variety of fields ranging from high viscous multi-functional ceramic fabrication to composite material fabrication [35].

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